Lightning Electromagnetics: Comparison of sprite initiation altitudes between observations and models

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Abstract

Simultaneous analyses of measured sprite initiation altitudes with predicted initiation altitudes from simulations enable an examination of our understanding of the sprite initiation mechanism and the modeling techniques to simulate this mesospheric electrical phenomenon. In this work, we selected a subset of sprites observed from Langmuir Laboratory, NM, a deployed vehicle in eastern Portales, NM, and a Duke University field station. The sprites observed from each location used high-speed imaging with time resolutions of at least 1 ms. Sprite initiation altitudes were determined by triangulation with Langmuir Lab and the deployed vehicle, while star field analysis determined the approximate measured initiation altitude at Duke. Using the electromagnetic radiation measured from low frequency sensors at Yucca Ridge Field Station and Duke University, we were able to extract the lightning source current moment waveform of sprite-producing lightning discharges. These source currents are applied as an input to a two-dimensional cylindrical finite-difference time-domain model to compute electric fields at different altitudes above the lightning discharge. The simulation results enable us to predict sprite initiation locations. We compare the measured initiation altitude of each sprite analyzed with these model predictions. The results across both data sets show a remarkably small discrepancy between the measured and predicted altitudes. For the Duke data, the maximum discrepancy is 6.59 km, while the Yucca Ridge data has a maximum discrepancy of 12 km. This result helps to develop confidence in our ability to robustly estimate the altitude of sprites from our own models.

1. Introduction

Sprites are high-altitude optical emissions produced by a subset of cloud-to-ground (CG) lightning discharges. Most sprites occur between 40 and 90 kilometers above thunderstorms as a result of conventional electric breakdown in the upper atmosphere [*Sentman et al.*, 1995; *Lyons*, 1996; *Pasko et al.*, 1997, 1998]. Since they were first documented in 1989 [*Franz et al.*, 1990], sprites have been regularly photographed and videoed by observers around the world [*Stanley et al.*, 1999; *Cummer et al.*, 2006; *McHarg et al.*, 2007]. For instance, since January 2008, over 150 sprites have been recorded annually at a Duke University field station alone.

Sprite analysis has advanced to the point where we may now estimate the electric field for a particular sprite above a thundercloud for a specific time, using various filtering and modeling techniques [*Hu et al.*, 2006, 2007; *Li et al.*, 2008]. Previous research has focused on modeling sprite streamers [*Liu et al.*, 2009, *Raizer et al.*, 1998] and true e-fields [*Hu et al.*, 2007], correlating video observations of sprite events with analyses of the models.

Initial sprite video observations involved charge-coupled device (CCD) sensors in digital cameras and this method was useful for determining the altitude range and color of sprites, but not for elucidation of finer sprite structures [*Sentman et al.*, 1995, *Wescott et al.*, 1998]. *Stanley et. al* [1999] first acknowledged the value of using high-speed video to confirm the accuracy of sprite modeling, specifically for sprite streamers measured with 1 ms time resolution. With 0.1ms time resolution [*McHarg et al.*, 2007] analyzed streamer details during initiation. Thus, the sprites set analyzed at Duke University were chosen specifically because high-speed video existed for those five sprites.

The goal of this work is to test our understanding of the physics behind sprites. We test our model for simulating electric fields above a thunderstorm by gauging how much it represents our understanding of the physics behind a single sprite—specifically, we compare the measured altitude and time from two data sets with the predicted simulation altitude and time from our own data analysis to confirm predictions made by *Li et. al* [2008].

We report and analyze in detail two sets of sprite events for which we have optical and data measurements. One set is from colleagues at the University of Alaska captured on 23 June 2007 and 3 July 2008 from Langmuir Laboratory, New Mexico and a deployed vehicle in Colorado, for which we have measured electromagnetic radiation from Yucca Ridge Field Station near Fort Collins, Colorado. The other set of sprites was captured from Duke University on 3 June 2009, for which we have high-speed video to help measure feature altitudes as well as measured electromagnetic radiation from our field sensors.

For each set of data, we use lightning location data obtained from the National Lightning Detection Network to act as the impetus for our modeling processes. From the information given in the lightning location data, we retrieve the waveform of the magnetic field in the azimuthal direction from the location and two vector magnetic fields and determine the precise time of the sprite-inducing lightning discharge and then run various deconvolution methods on these fetched files to extract a current moment waveform [*Cummer and Inan,* 2000]. Then, we are able to compute the electric fields above the lightning discharge using an FDTD model only after thoroughly accounting for the lightning-to-sprite delay time [*Hu et al.,* 2006]. Through the high-speed images captured at Duke, we illustrate how we determined the feature altitudes of each of the five events. After calculating the predicted altitudes, we were able to make plots of the normalized electric field [*Hu et al.,* 2007]. Through these plots, we determine the discrepancy between measured and predicted altitudes.

2. Instrumentation and Method of Analysis

Measured broadband low-frequency electromagnetic radiation data was used in this work from two sites: Yucca Ridge Field Station and Duke University. Yucca Ridge Field Station (40.702°N, -105.031°E), has one electric field sensor to record the vertical electric field of lightning discharges and two magnetic field sensors to capture the corresponding full horizontal field. The sensors were built by Quasar Federal Systems, Inc. [*Cummer et al.,* 2005]. At the Duke University field site (35.864°N, -79.101°E), two pairs of magnetic induction coils record the horizontal magnetic field from in the ULF range (0.1 – 500Hz, built by EMI, Inc.) and VLF range (100Hz – 25kHz, custom designed). The NLDN provided each of the return stroke locations for lightning used in this work. Additionally, to perform our simulations, we determine the azimuthal magnetic field defined by a cylindrical coordinate system with the origin at the location of the lightning discharge. This can be determined by knowing the lightning location and two orthogonal horizontal measurements of the magnetic field from any pair of coils described above [*Li et al.,* 2008].

The instruments used by the University of Alaska include two high-speed intensified Phantom 7 imagers as well as two Watec 902H2 cameras. One of each was used at each location

(Langmuir Lab, NM and Portales, NM) for video uniformity. Additionally, the two cameras as well as the GPS system in Portales, NM were run on car power because the station was run out of a vehicle. There are two sets of cameras used because two geographic locations are necessary for triangulation. Viewing directions for each of the cameras was verified using background star analysis.

At the Duke site, two cameras were used to record the optical emissions from sprite events on 3 June 2009. First, a Watec 902H2 Ultimate monochrome low-light gather camera capable of imaging near infrared visibility was used to capture a field of view (50° wide) that included background stars and the horizon with an image size of 720 x 480 pixels. The high-speed camera was a Vision Research Phantom 4.2 high-speed imager coupled to an ITT Gen III image intensifier with spectral response from 450 to 900 nm. The phosphor persistence of this intensifier was measured to have a half-life of 0.35–0.70 ms, depending on the source brightness [*Cummer et al.,* 2005]. For the five events captured on the Phantom, images were captured at 500, 1000, and 2000 frames per second with a constant image size of 512 x 512 pixels and field of view 7.16° wide. An external GPS-synchronized IRIGB time code computes an integration time and the camera stamps this time onto each image with a time accuracy of 10 microseconds. The resulting data set comprises high resolution images and wideband magnetic measurements.

As mentioned in the introduction, we extract the current moment from the magnetic field data using deconvolution methods described by *Cummer and Inan* [1997, 2000] and *Cummer* [2003]. Once we have the current moment waveform extracted from the source lightning, we may simulate the electric fields above a source lightning discharge as a function of time (ms) and altitude (km) with the 2D FDTD model. Then we normalize this electric field against the air-breakdown field at different altitudes (E/E_k), using the same procedure as *Hu et al.* [2007] in order to plot the data.

The measured altitudes presented here are from one of two sources: Altitudes provided to us from the University of Alaska or our own estimations. Our estimations are made using background star fields captures with the Watec camera. We do not directly use the high-speed images because the Phantom has too small of a field of view to be able to see stars. We determined the altitudes of stars and the corresponding pixels that bound each of the five events and then used interpolation to determine the pixels that bound the sprite. Using the high-speed images, the initiation altitude of the sprite was then determined by knowing the altitude of the sprite bounds and interpolating to the bright core. The effect of atmospheric refraction was taken into account. We also made the assumption that the sprite is directly above the NLDN reported location of the source lightning discharge. However, the unknown horizontal offset between sprites and their parent lightning discharge, expected to be a few tens of kilometers by *Wescott et. al* [2001] makes for an overall altitude uncertainty of +/- 3 km, corresponding to an offset of +/-10 km for lightning discharges 300-400 km from the observation site [*Li et al.,* 2009]. The reported source lightning in this analysis for events captured at Duke was between 312 and 369 km. One of these five events lacked an NLDN parent stroke, so we used the predicted initiation altitude (71 km) to find the great circle distance from the station to the predicted stroke, at 330 km. However, because this event lacks NLDN data, there is no way to obtain an accurate distance from the station to the parent lightning stroke. In this case, we used the distance obtained from the first high-speed event because the images of the first and second sprite events were relatively in the same place in the sky.

3. Results from Triangulated Events

We began our analysis with all triangulated sprite events provided to us occurring on two separate dates in the southwestern United States. This information contained lightning time, sprite time, time delays of each sprite as well as initiation altitudes. We began with 30 downward streamer events. We analyzed downward streamer events because downward streamers initiate first after the parent lightning stroke [*Cummer et al.,* 2006]. Of these 30 events, 23 were labeled with triangulated initiation altitudes, and of these 23 events, two were deemed “weak” by colleagues and thus were eliminated these events from the analysis, leaving 21 events. Finally, of these 21 events, we had the necessary low frequency data for 18.

For one event occurring on 23 June 2007 we were able to successfully use Duke ULF data for the analysis. However, for all other events (occurring on 3 July 2008), we were unable to use Duke ULF data because it was missing from our records and thus used ELF data from Yucca Ridge Field Station. With the results from the FDTD simulation, plots of the normalized electric field were developed that illustrate the measured triangulated altitudes with the simulation predicted altitudes.

The time delay shown is the time between the parent lightning discharge and sprite initiation. A correction to the time delay was made to account for the propagation time between the sprite location and the location of the field observations. We determined the lightning time by using our measured data (Yucca Ridge and Duke ULF) and the propagation delay included in the data. Once we knew the time delay, we were able to place points on our plots corresponding to the measured time and the predicted simulation time.

In each figure below and throughout this work, the x-coordinate of the marker corresponds to the calculated lightning-to-sprite delay time and the y-coordinate corresponds to the measured and predicted initiation altitudes in red and white markers, respectively. The predicted altitude is defined by taking the largest e-field at the given time as the point of initiation of the sprite. In order to plot our predicted altitude, we used the time delay from the table and then found the greatest normalized electric field at that time. A white marker was placed in each plot corresponding to this simulation-predicted altitude. Figure 1 illustrates measurements for the single event on 23 June 2007 occurring at 5:10:10.601 UT. These measurements include the azimuthal (tangential) magnetic field from a sprite-producing lightning strike as measured at Duke University, the extracted current moment and total charge moment waveforms, and the FDTD-simulated vertical normalized electric field between 60 km and 90 km altitude. The color intensity of the plot represents the amplitude of the normalized electric field. As visible in Figure 1c, the discrepancy between measured and predicted results is 1 km at a 2.5ms delay between lightning strike and sprite.

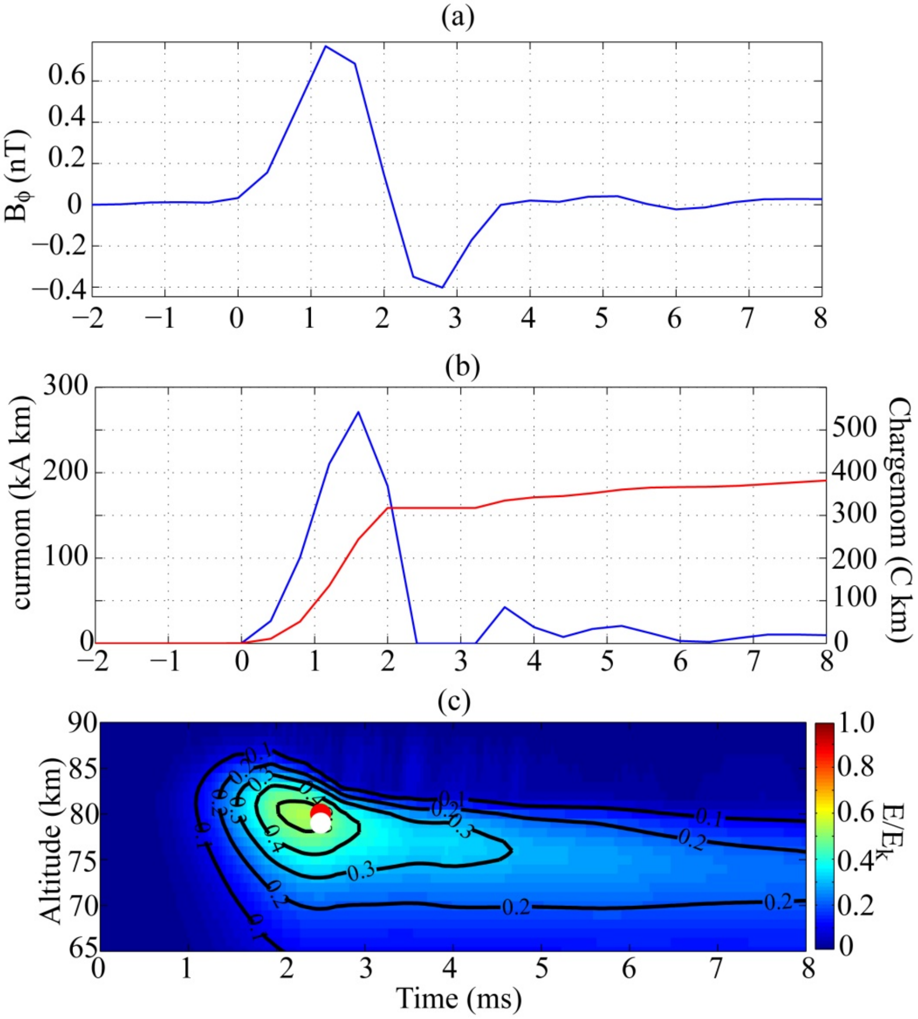

Figure 1. (a) The azimuthal magnetic field at Duke University. (b) The extracted current moment waveform and total charge moment waveform for the event. (c) The simulated normalized e-field plot showing lightning-to-sprite time delay of 2.5 ms, with measured initiation altitude (80 km) and predicted initiation altitude (79 km).

Figure 2 below illustrates the FDTD simulation results for three other triangulated events initiating between 45 and 85 km. Figure 2a shows an event with three downward sprite streamers, initiating 141.80, 143.48, and 143.96 ms following the lightning strike. The corresponding measured and predicted initiation altitudes of these streamers are 66 and 72 km, 65 and 72 km, and 65 and 72 km, respectively. In Figure 2b, there are two downward streamers initiating 54.24 and 67.18 ms following the lightning strike. The corresponding measured and predicted initiation altitudes of these streamers are 75 and 71 km and 68 and 68 km, respectively. For Figures 2a-b, we have now shown that with distinct normalized electric fields at the time of sprite initiation, the discrepancy between our model predictions and the actual measured altitudes is 7 km or fewer.

In Figure 2c, there are four events. For three of these events, the time delays and discrepancies are similar to Figure 2a-b. However, the final event at a time delay of 128.05 ms has an absolute maximum field below the measured initiation altitude, but a local maximum (a few ms later) above it. By using the absolute maximum and not the locally maximum e-field, there is a large discrepancy between measured and predicted initiation altitudes. Therefore, it is possible that the sprite was observed to first initiate at 67 km, but could have been predicted to initiate between 65 and 80 km due to the local maximum e-field at that time.

The measured altitudes for all events as well as discrepancies between measured and predicted altitudes are plotted in Figure 6 following discussion of Duke high-speed data.

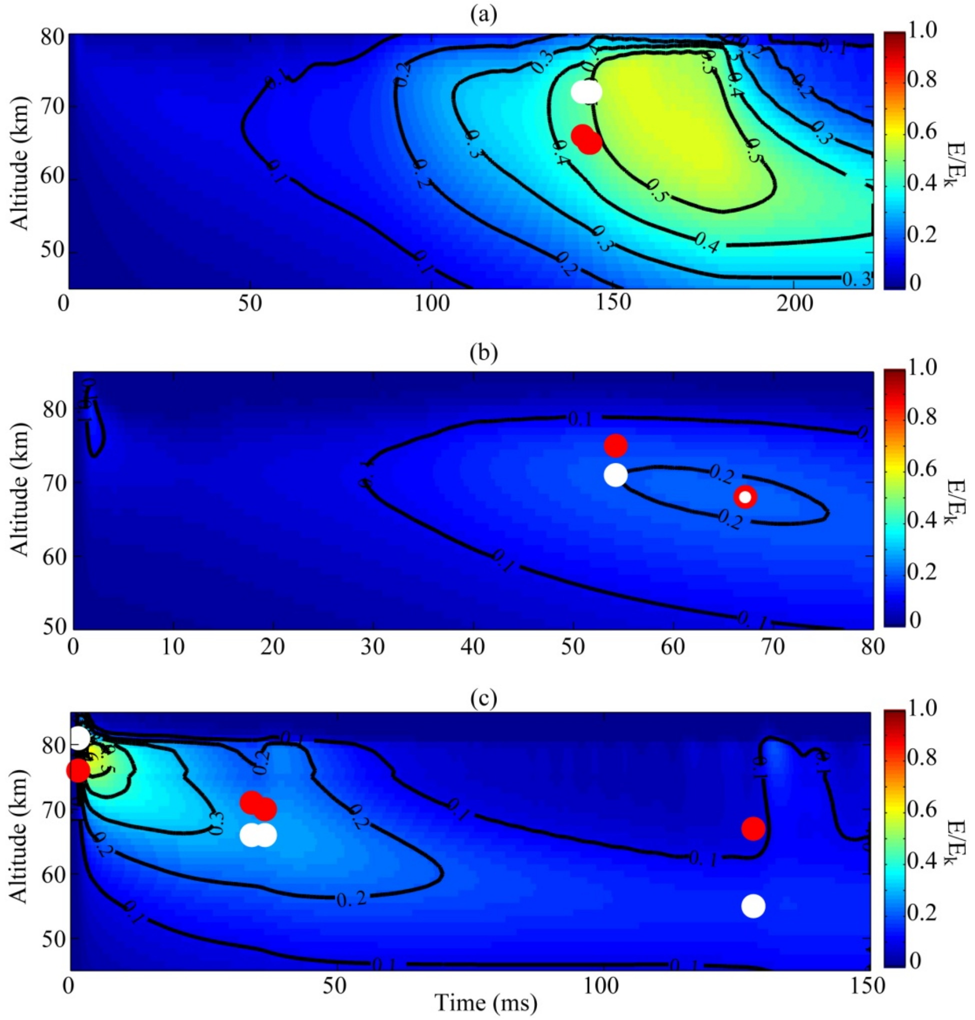

Figure 2. Simulated electric fields above the lightning discharge. (a) Event 3 results. (b) Event 6 results. (c) Event 2 results.

4. Results from Duke High-Speed Video

On 3 June 2009, our high-speed camera captured five sprites produced by thunderstorms between 300 and 400 km away from our observation site. For three events below (Figures 5-7), there is an FDTD plot showing the simulated electric field above the lightning discharge. In addition to markers indicating initiation altitudes, there is a vertical bar centered on the measured altitude indicating an uncertainty of +/- 3km.

Figure 3 shows the simulation result for the first sprite recorded at 500 fps. The sprite initiated 39 ms after the return stroke at 67.2 ± 3 km altitude estimated from high-speed images while the simulation altitude is predicted at 70 km. The sprite initiation altitude is measured at 67.2 km and the simulation result places the altitude at 70 km. The source lightning was determined to be 312 km from the field site. The estimated initiation altitude is represented by a red marker with an altitude uncertainty bar of ±3 km.

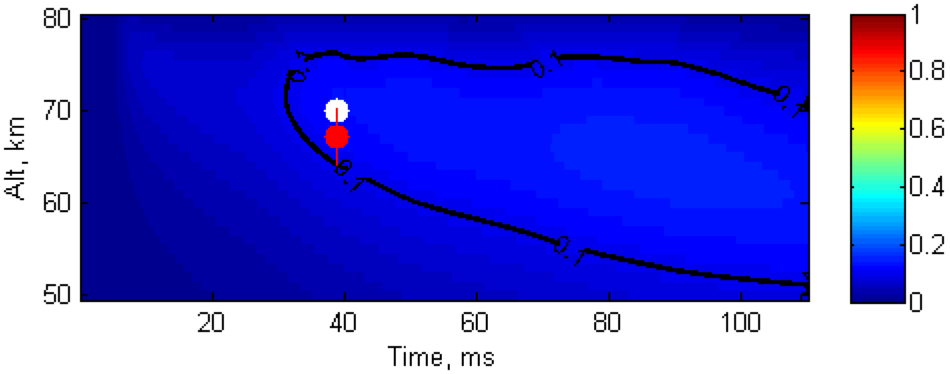

Figure 3. FDTD result for a sprite recorded on 3 June 2009 at 03:31:06.893 UT

The second sprite was recorded at 03:39:58.581 UT, at 500 fps. The sprite initiated 95.5 ms after the return stroke at 69.66 ± 15 km altitude estimated from high-speed images while the simulation altitude is predicted at 71 km. There is a greater uncertainty for this event because the NLDN contained no record of the source lightning that produced this event.

Figure 4 shows the simulation result for the third sprite recorded at 500 fps. The sprite initiated 17.7 ms after the return stroke at 72.7 ± 3 km altitude estimated from high-speed images while the simulation altitude is predicted at 72 km. The source lightning was 359 km from the field site.

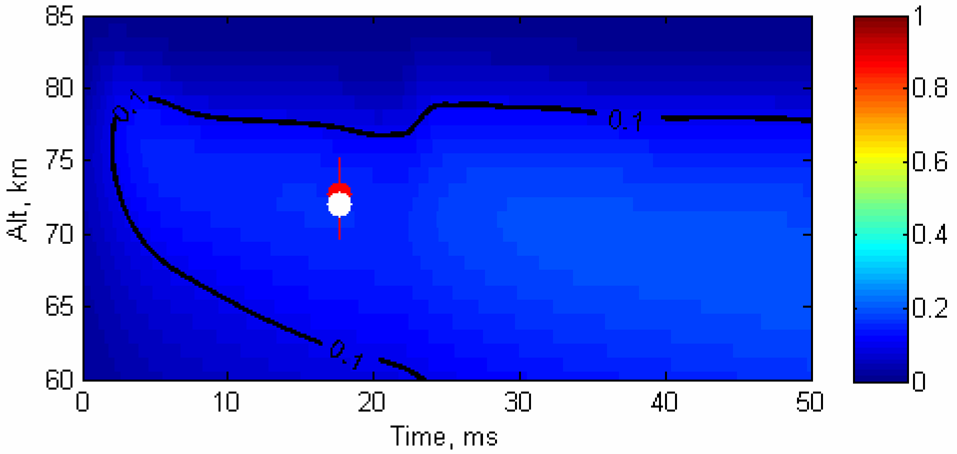

Figure 4. FDTD result for a sprite recorded on 3 June 2009 at 03:53:52.980 UT.

A fourth sprite event was recorded at 04:04:51.737UT at 1000 fps. The sprite initiated 6.1 ms after the return stroke at 74.156 ± 3 km altitude estimated from high-speed images while the simulation altitude is predicted at 75 km. The source lightning was 340 km from the field site.

Figure 5 shows the simulation result for the fifth sprite recorded at 2000 fps. The sprite initiated 3.5 ms after the return stroke at 71.41 ± 3 km altitude estimated from high-speed images while the simulation altitude is predicted at 78 km. The source lightning was 368 km from the field site.

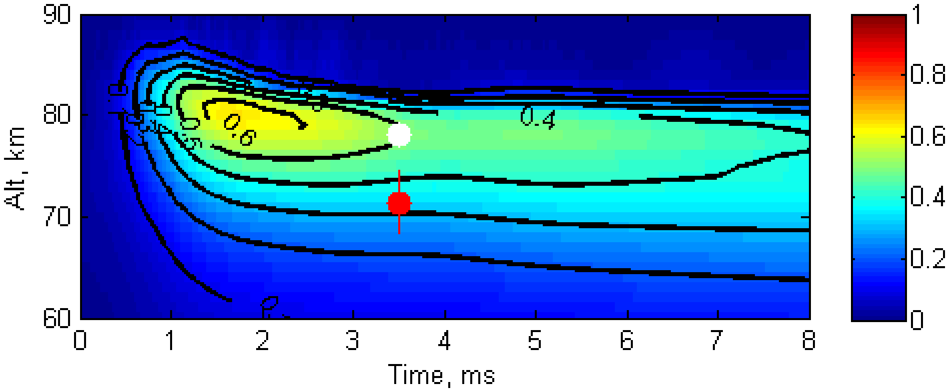

Figure 5. FDTD result for a sprite recorded on 3 June 2009 at 04:18:13.443 UT.

For each of these five examples, the simulated-predicted altitudes agree very well with the estimated initiation altitudes within 7 km. For four of five high-speed events, the discrepancy is within 3 km. Given the uncertainty introduced by each stage of this analysis, these are exceptional results.

Below, Figure 6 shows a cumulative plot of all results. The first subplot illustrates the measured altitudes for each event. Points in blue represent events that had the discrepancy between measured and predicted initiation altitudes change with a time shift of a few milliseconds. The second subplot illustrates the discrepancy with the stipulation that the difference is determined by measured – predicted altitude. Analysis of the plot reveals that shorter delayed sprites generally initiate at greater altitudes than sprites with a larger time delay, which is what we expect from *Li et al.* [2008]. Additionally, the predicted altitude value was often smaller than the measured value. This means that there is a bias towards a higher prediction value, which is also acceptable given that sprite initiation modeling is quite complex. In Figure 8, the maximum discrepancy is 12 km and the minimum is 0 km. Because the triangulated altitudes have a small enough altitude error to be negligible, we can safely assume that the discrepancy for those events results from a reported time issue or a local maximum e-field (as opposed the absolute e-field). However, there are still markers that are not in close agreement. These events occur at a time when the electric field is vertically uniform and there are very low predicted e-field ($E/E_k < 0.1$)at the time of the downward streamer. Therefore, the sprites could have initiated over a wide range of altitudes and there is a great uncertainty for the predicted field altitudes.

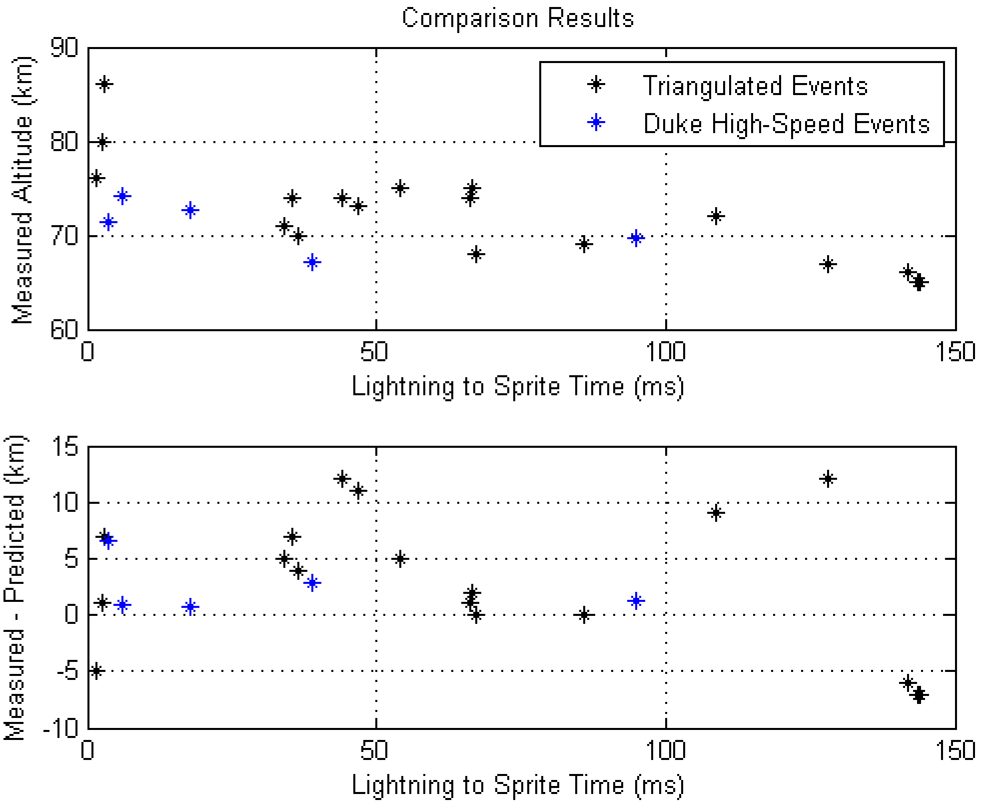

Figure 6. Data results from both triangulated and Duke high-speed analysis. (a) Measured altitudes of all events analyzed. (b) The discrepancy between measured and predicted initiation altitudes.

5. Summary

Coordinated analysis of measured sprite initiation altitudes and simulation-predicted altitudes are reported and analyzed. First, the data for events captured from two locations in the southwestern United States are presented through FDTD plots and the discrepancies between the observed and predicted altitudes are shown to be small. Explanations are given for the larger discrepancies documented and for the discarding of events that were not ideal. Next, the data for events captured at Duke University are presented through FDTD plots and the discrepancies are shown to be within the error range. For the Duke events, the discrepancies between measured and predicted altitudes ranged from 0 to 6.59 km, while the triangulated events ranged from 0 to 12 km. Of the five Duke events, only one was predicted to be outside the error range, and for the triangulated events, there were a couple of outliers that were predicted to be 12 km from the measured altitudes, but for the most of the events, the discrepancy was within 5 km. These results further confirm the initiation mechanism and QE model as well as the correctness of the FDRD model we used. Providing an analysis for the methods with which we analyze these optical events lay the foundation for increased understanding of sprites through further detailed analyses.

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